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RESEARCH MEMORANDUM

PERFORMANCE OF FIVE LOW-TEMPERATURE-RATIO RAM-JET COMBUSTORS OVER RANGE OF SIMULATED ALTITUDES

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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RESEARCH MEMORANDUM

PERFORMANCE OF FIVE LOW-TEMPERATURE-RATIO RAM-JET COMBUSTORS OVER RANGE OF SIMULATED ALTITUDES

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SUMMARY

The analysis of direct-connect performance data obtained with five flame holders of various gutter and can types operated in a 20-inch-diameter ram-jet engine at simulated Mach number 3 revealed that the specific impulse of each of the flame holders was about the same. Small differences in performance did not indicate appreciable superiority of any one type.

The combustion-chamber length had a marked effect on specific impulse. Reduction of combustion-chamber length from 86 to 56 inches resulted in reductions of impulse of 10 to 30 percent. Altitude increases affected the performance of both long and short combustors in about the same manner.

INTRODUCTION

As part of a program being conducted at the NACA Lewis laboratory to devise ram-jet combustors suitable for long-range missiles, the performance of five flame holders was investigated in a 20-inch-diameter ram jet over a range of combustor pressures from 500 to 1800 pounds per square foot. The investigation was conducted to determine which of the flame holders, if any, had superior characteristics for high-altitude cruise operation. Each of the five flame holders incorporated a fuel-air-mixture control sleeve (ref. 1) designed to give good performance at over-all fuel-air ratios of approximately 0.02. The fuel-mixture distributions used with each flame holder were essentially the same, so that differences in performance are primarily due to flame-holder effects. The investigation was conducted by the direct-connect technique and simulated a flight Mach number of 3. Four of the flame holders have previously been tested at Mach number 3 in a free-jet and the results are given in references 2 to 4. The flame holders previously investigated include a can-type flame holder, a 2-ring V-gutter flame holder with a large central pilot, a sloping-gutter flame holder with a large central pilot, and an annular-pilot flame holder. The fifth flame holder was a 1-ring V-gutter with a small central pilot.

The combustor efficiencies and combustor total-pressure ratios were determined for each of the flame holders, and the data were used to compute values of specific impulse so that direct comparisons might be made. The effect of changes in combustion-chamber length upon the performance of the can flame holder and the annular-pilot flame holder over a range of combustor pressures was also determined.

SYMBOLS

The following symbols are used in this report:

A	combustion-chamber cross-sectional area, 2.18 sq ft
C_V	exhaust-nozzle velocity coefficient
f/a	combustor fuel-air ratio
$(f/a)_h$	air-heater fuel-air ratio
$(f/a)_i$	ideal fuel-air ratio
$(f/a)_s$	stoichiometric fuel-air ratio
g	acceleration due to gravity, ft/sec^2
I	specific impulse, sec
V_j	exhaust jet velocity
V_O	flight velocity
W_a	engine air-flow rate, lb/sec
W_f	engine fuel-flow rate, lb/sec
τ	combustor total-temperature ratio, $\frac{\text{combustor-outlet total temperature}}{\text{combustor-inlet total temperature}}$

APPARATUS

Test Facility and Engine

A diagram of the test engine installed in the altitude facility is shown in figure 1. The facility was converted from a free-jet test

chamber to a directly connected facility by closing the jet diffuser with plates. In operation, air was ducted subsonically to the annular inlet formed by the centerbody and outer shell of the engine. An air heater consisting of turbojet combustor cans was installed in the inlet-air line. Heating of the air was accomplished by mixing the hot exhaust gas with bypassed air. The contamination of the air due to the air heater corresponded to a fuel-air ratio of about 0.008.

The test engine had a maximum inside diameter of 20 inches and incorporated a flight-type diffuser that was originally intended for free-jet operation. The annulus formed by the diffuser centerbody and the diffuser cowl was choked for all operating conditions of this investigation. The engine was equipped with a convergent exhaust nozzle, the throat area of which was 55 percent of the engine cross-sectional area. Variation of combustor length was accomplished by inserting or removing a 30-inch section of the combustion chamber. This provided lengths of 86 and 56 inches measured from the aft end of the centerbody to the exhaust-nozzle inlet.

Ignition was accomplished by means of an electric spark in the pilot zone of the flame holder. Power for the spark was supplied by a condenser-discharge apparatus similar to a type commonly used with turbojet engines. A throttling valve downstream of the engine exhaust nozzle was used to reduce the flow velocities in the engine in order to facilitate ignition.

The fuel used in the engine and the air heater was MIL-F-5624A, grade JP-4.

Flame Holders and Associated Fuel Injectors

Five flame holders were tested in this investigation. Because the fuel-injection systems were not the same for each of the flame holders, the fuel system is described in conjunction with the flame holder with which it was tested. Each of the fuel systems provided an essentially uniform mixture of fuel and air for the design fuel-air ratio, so the effects of these variations in fuel system are negligible.

Can flame holder. - Details of the can-type flame holder are shown in figure 2(a). The can was 41.8 inches long and had an included angle of 16.5°. The sum of the hole areas in the can was equal to 1.17 of the combustion-chamber cross-sectional area. A fuel-mixture control sleeve enclosing 49 percent of the open area of the can was attached to the flame holder.

Fuel was injected into the engine through internal manifolds, which are shown in the detail of figure 2(a). Each of the three inner manifolds

had six spray bars that provided normal fuel injection from two opposed holes. The outer manifolds had spray holes drilled in the manifold, but these manifolds were not used in this investigation. A single 12-gallon-per-hour conical spray nozzle was located in the center of the upstream end of the can to provide pilot fuel. Only moderate amounts of pilot fuel were used (2 to 3 percent of over-all stoichiometric fuel flow) for maintaining satisfactory blow-out limits.

Two-ring V-gutter flame holder. - The details of the 2-ring V-gutter flame holder are shown in figure 2(b). A large central pilot burner, consisting of a modified turbojet burner liner, was affixed to the blunt end of the diffuser centerbody. The upstream end of the burner liner, which contained primary-air louvers, was removed to provide a base diameter campatible with the size of the centerbody. A pilot fuel-mixing control sleeve surrounded the burner liner, and pilot fuel was sprayed inward from the upstream end of the sleeve. The fuel was confined within the sleeve, thus permitting separate control of the fuel-air mixture within the pilot burner. Approximately 12 percent of the engine air flow passed through the pilot burner.

The flame holder consisted of nine radial and two circular V-gutters, as shown in figure 2(b). The total flame-holder blockage, including the pilot burner, was 60 percent of the combustion-chamber cross-sectional area.

The main fuel-injection system had two parts, each accommodating annular zones on either side of a cylindrical control sleeve. The control sleeve was designed to capture approximately 28 percent of the engine air flow for the inner zone. Thus, the pilot and inner-zone air flow involved 40 percent of the engine air flow. The fuel-injection system for the inner zone was placed 19.4 inches from the plane of the flame holder and consisted of 16 spray bars having four holes directed circumferentially. The fuel-injection system for the outer zone, which was not used in this investigation, was located 17.3 inches upstream of the plane of the flame holder and consisted of 16 spray bars, each with two holes spraying circumferentially.

Sloping-gutter flame holder. - The details of the sloping-gutter flame-holder configuration are presented in figure 2(c). The pilot burner and its fuel-injection system were the same as for the 2-ring V-gutter flame holder. The flame holder consisted of two sets of channel-shaped sloping gutters interconnected by a conical sleeve. The inner set had six equally spaced gutters inclined at 30° to the combustor axis. The outer set had 12 equally spaced gutters also inclined at 30° to the combustor axis. A fuel-mixing control sleeve joined the flame holder at the outer end of the inner set of gutters. The flame-holder and control-sleeve combination was designed to pass 40 percent of the engine air inside the control sleeve. The main fuel system was the same as for the 2-ring V-gutter flame holder.

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One-ring V-gutter flame holder. - The details of the 1-ring V-gutter flame holder are given in figure 2(d). The flame holder consisted of a single-ring gutter whose section was a 1.5-inch-wide "V" and which had a diameter of 13.7 inches at the apex of the V-section. Three 1.5-inch-wide radial gutters connected the ring gutter to a central pilot can 6.4 inches in diameter and $7\frac{3}{4}$ inches long. A cylindrical skirt was attached to the downstream outer edge of the ring gutter and extended 6 inches downstream into the combustion chamber. Two rows of 20 holes 1/2 inch in diameter were punched in the pilot can near the downstream end. A single 12-gallon-per-hour conical spray nozzle was located in the center of the upstream end of the pilot can to provide pilot fuel. A fuel-mixing control sleeve was joined to the flame holder at the vertex of the circular V-gutter.

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The fuel-injection system used with the 1-ring V-gutter flame holder was made up of spray bars having two holes directed normal to the air flow. Both inner and outer zones had sets of 15 bars with spray holes of 0.062-inch diameter. The inner-zone spray bars were located 21.0 inches from the plane of the flame holder. Each inner-zone bar had an external metering orifice 0.032 inch in diameter. The outer-zone spray bars (not used in this investigation) were located 16.6 inches upstream of the plane of the flame holder.

Annular-pilot flame holder. - The details of the annular pilot flame holder are shown in figure 2(e). The flame holder had an annular pilot zone formed by a cylindrical surface and a conical surface. The outer (cylindrical) surface had three rows of 1/2-inch-diameter holes near the upstream end. The inner (conical) surface was cut longitudinally at 18 positions, and the resulting strips were bent along their length to form channels with the concave side toward the pilot zone. These channels were secured at the downstream end by a circular V-gutter, which provided an additional flame seat. A fuel-mixing control sleeve extended upstream from the apex formed by the junction of the cylindrical and conical surfaces.

Pilot fuel was introduced into the pilot zone by means of five spray bars having two holes spraying circumferentially. The spray holes were 0.040 inch in diameter. An external metering orifice 0.021 inch in diameter was provided for each bar.

The main fuel-injection system was the same as that used for the 1-ring V-gutter flame holder. The inner-zone spray bars were located 12.1 inches upstream of the flame-holder apex. The outer-zone spray bars, which were located 7.7 inches upstream of the flame-holder apex, were not used in this investigation.

Instrumentation

The instrumentation used in this investigation is shown in figure 1. A total-pressure survey was made at station 4 (exhaust-nozzle inlet) for use in computing air flow and efficiency. The static pressure at station 2 was measured through three wall orifices for determining combustor-inlet Mach number and total pressure. The temperature of the inlet air was found by means of a thermocouple rake in the surge tank ahead of the engine inlet. Fuel-flow rates to the air heater and engine were measured with calibrated rotameters. The air-flow rate to the air heater was found by means of a flat-plate orifice meter.

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PROCEDURE

Simulated Flight Conditions

This investigation was conducted with an inlet-air temperature of 1100° R, which is the standard total temperature experienced in flight at Mach number 3 at altitudes above the tropopause. The engine air flow was varied from 3.2 to 10.2 pounds per second per square foot of combustion-chamber area by varying the pressure ahead of the choked engine inlet. This range of air flow corresponds approximately to altitudes of 98,000 to 72,000 feet for a ram-jet engine equipped with an exhaust nozzle with a throat area 55 percent of the combustion-chamber area and a diffuser giving 0.6 total-pressure recovery at Mach number 3 and operating with a total-temperature ratio of 2.0.

Ignition of the engine was accomplished by throttling the engine exhaust flow (to reduce combustor velocities), initiating pilot fuel flow, and then energizing the electrical ignition system. At low combustor pressures, inner-zone fuel flow in amounts giving an over-all fuel-air ratio of 0.02 was helpful in starting. After starting, the exhaust throttle valve was opened until the exhaust nozzle became choked.

The data were obtained by maintaining a fixed engine air flow while varying the engine fuel flow to cover a complete range of fuel-air ratios. Some experimentation was required with each flame holder to determine the schedule of pilot fuel that gave best performance over the range of fuel-air ratios investigated.

Calculations

Engine air flow was determined by using the exhaust nozzle as a metering orifice. A nozzle discharge coefficient of 0.985 was assumed. Engine fuel-air ratio was calculated as the ratio of engine fuel flow to the unburned air flow entering the engine. A detailed derivation

is presented in reference 2, which resulted in this expression for fuel-air ratio:

$$f/a = \frac{W_f}{W_a}\left[\frac{1 + \left(\frac{f}{a}\right)_h}{1 - \frac{\left(\frac{f}{a}\right)_h}{\left(\frac{f}{a}\right)_s}}\right]$$

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The combustor efficiency was taken as the ratio of ideal fuel-air ratio to actual fuel-air ratio, where the ideal fuel-air ratio was that necessary to obtain, with an ideal combustion process, the total pressure measured at the exit of the combustion chamber for the air flow under consideration. The particular method used to determine the ideal fuel-air ratio is given in reference 2.

The combustor-inlet total pressure was calculated from values of wall static pressure at station 2, engine air flow, and measured flow area. The combustor total-pressure ratio was calculated as the combustor-outlet total pressure (station 4) divided by the combustor-inlet total pressure (station 2).

The specific impulse was calculated as the ratio of the net thrust in pounds to the engine fuel flow in pounds per second:

$$I = \frac{C_V V_j\left(1 + \frac{f}{a}\right) - V_0}{g\,\frac{f}{a}}$$

RESULTS

Flame-Holder Performance

Each of the five flame holders was designed to give best efficiency at a combustor total-temperature ratio of 2.0. The general performance characteristics of the five flame holders are presented in figure 3, where combustor efficiency, combustor total-pressure ratio, and combustor-exit total pressure are plotted against ideal fuel-air ratio $(f/a)_i$ for various values of unit air flow W_a/A. Lines of constant fuel-air ratio are included on the efficiency plots for reference. An abscissa scale of total-temperature ratio τ is also included.

The data of references 2 to 4 show the results of operation with fuel injection in the inner zone (low τ) and with fuel injection in both zones (high τ). Good performance was obtained with both, but discussion herein is limited to the low total-temperature ratios that are of interest for cruise operation.

Reference to the data of figure 3 reveals that the τ for which peak combustor efficiency occurred is not the same at all pressures. A long-range missile would probably require operation at a constant value of τ for a range of cruise altitudes. Therefore, applying one of these combustors to a missile would involve the selection of a compromise value of total-temperature ratio that would give good combustor efficiency over the widest range of pressures. Values of τ satisfying the above requirement were selected for each combustor and are presented in table I along with the corresponding combustor total-pressure ratio.

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The parameter chosen to compare the performance of the five flame holders over a range of combustor pressures was specific impulse, which is directly proportional to the range potential of the engine and combines in a single parameter the two parameters, combustor efficiency and combustor total-pressure ratio. The specific impulse, however, depends somewhat upon the combustor total-temperature ratio. Therefore, a difficulty arises because the τ values selected to represent the capabilities of each flame holder (table I) are not the same in each case. To avoid this difficulty, an analysis was made that, in effect, adjusted the performance of each flame holder to a common τ of 2.0. Further details of the analysis appear in the appendix.

The results of the analysis of the data of figure 3 are presented in figure 4, where specific impulse is plotted against altitude for the five flame holders. A scale of combustor-inlet total pressure is also included for reference. In general, the impulse of each of the flame holders was about the same for the range of this investigation. Values of impulse ranged from about 1400 seconds at 96,000 feet to as high as 1730 seconds at 74,000 feet. The greatest difference in performance between various flame holders occurred at 74,000 feet, where the can flame holder had an impulse 8 percent higher than the annular-pilot flame holder. The two-ring flame holder had from 2 to 7 percent lower impulse than the annular-pilot flame holder in the range of altitudes from 80,000 to 91,000 feet. This low performance of the two-ring flame holder is attributed to the relatively short combustion-chamber length (55 in.), which resulted from the space requirements of the large pilot burner. The relatively small differences in performance between flame holders does not indicate appreciable superiority of any one type.

Effect of Combustion-Chamber Length on Flame-Holder Performance

In order to determine the effect of combustion-chamber length on combustor performance as the pressure is reduced, the can and annular-pilot flame holders were tested with the combustion-chamber length reduced by 30 inches (fig. 5). The specific impulse for these shorter combustors was computed from these data by the same procedure as previously discussed. The compromise values of τ selected to represent the low-temperature-ratio operation of the flame holders are given in table I.

The results of the impulse calculation are presented in figure 6. Curves from figure 4 giving the performance with the long combustion chamber are reproduced for comparison. The impulse of the can flame holder (fig. 6(a)) with the short combustion chamber (56 in.) ranged from 1320 to 1420 seconds over the altitude range from 86,700 to 81,500 feet. This is approximately 14 percent less than was obtained with the 86-inch combustion-chamber length. However, within the range of altitudes investigated, the slope of the two curves appears to be about the same.

For the annular-pilot flame holder (fig. 6(b)), the impulse was reduced from 7 to 10 percent by using the short combustion chamber for the altitude range from 81,300 to 93,000 feet. In this range of altitudes, the slope of both curves is approximately the same. However, at altitudes above 93,000 feet the impulse of the short combustor fell off rapidly, until at 97,000 feet the impulse was 30 percent lower than for the long chamber. Therefore, it appears that, although the long combustors experienced about the same decay of performance with increased altitude as the short combustors up to 94,000-feet altitude, the short-combustor performance did fall off more radidly at extreme altitudes.

SUMMARY OF RESULTS

The following results were obtained when five 20-inch-diameter ramjet combustor flame holders were investigated to discover the one most satisfactory for operation at high cruise altitudes:

1. In general, the specific impulse of each of the five flame holders was about the same for the range of simulated altitudes of this investigation. Small differences in performance between flame holders did not indicate a superiority of any one type.

2. A can flame holder and an annular-pilot flame holder were tested with the combustion chamber shortened from approximately 86 inches to approximately 56 inches. The impulse of the can flame holder was decreased approximately 14 percent by this reduction. The impulse of the annular-pilot flame holder was lowered approximately 10 percent for simulated altitudes up to 93,000 feet. At higher altitudes the difference increased until the short combustor had an impulse 30 percent lower than the long combustor.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 20, 1954

APPENDIX - DETAILS OF ANALYSIS OF DATA

As mentioned in the RESULTS, the combustor total-temperature ratios τ selected to represent the capabilities of the five flame holders were not the same. Furthermore, the specific impulse depends somewhat upon the value of τ. Therefore, a comparison of flame holders operating at different values of τ would be misleading. Accordingly, an analysis was made in which the schedule of combustor efficiency and combustor total pressure associated with the τ selected for each flame holder was assumed to apply if the same flame holder were operated at $\tau = 2.0$. It is believed that the τ for peak efficiency can, in practice, be shifted over a small range without altering the combustor efficiency or combustor total-pressure ratio appreciably. This would be done by changing the control-sleeve diameter at the flame holder and thus changing the amount of air flowing within the sleeve.

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The schedules of combustor efficiency and combustor total pressure pertaining to the values of τ in table I are presented in figure 7, where combustor efficiency is plotted against combustor-exit total pressure for each flame holder.

A flight Mach number of 3 and a diffuser total-pressure recovery of 0.6 were picked for the calculation of impulse, and it was assumed that the engine was equipped with a completely expanded convergent-divergent exhaust nozzle having a velocity coefficient of 0.95.

The thrust output of the various engines analyzed in the foregoing manner would not be the same if all engines had the same diameter because of the variations of combustor total-pressure ratio between the different flame holders. This will not materially alter the conclusions of the analysis, however, because the changes of engine size required to compensate for this effect are small and would have negligible effect on the external aerodynamics of the engine nacelle.

REFERENCES

1. Trout, Arthur M., and Wentworth, Carl B.: Free-Jet Altitude Investigation of a 20-Inch Ram-Jet Combustor with a Rich Inner Zone of Combustion for Improved Low-Temperature-Ratio Operation. NACA RM E52L26, 1953.

2. Smolak, George R., and Wentworth, Carl B.: Altitude Investigation of Can-Type Flame Holder in 20-Inch-Diameter Ram-Jet Combustor. NACA RM E54D08, 1954.

3. Henzel, James G., Jr., and Wentworth, Carl B.: Free-Jet Investigation of 20-Inch Ram-Jet Combustor Utilizing High-Heat-Release Pilot Burner. NACA RM E53H14, 1953.

4. Henzel, James G., Jr., and Trout, Arthur M.: Altitude Investigation of 20-Inch-Diameter Ram-Jet Engine with Annular-Piloted Combustor. NACA RM E54G12, 1954.

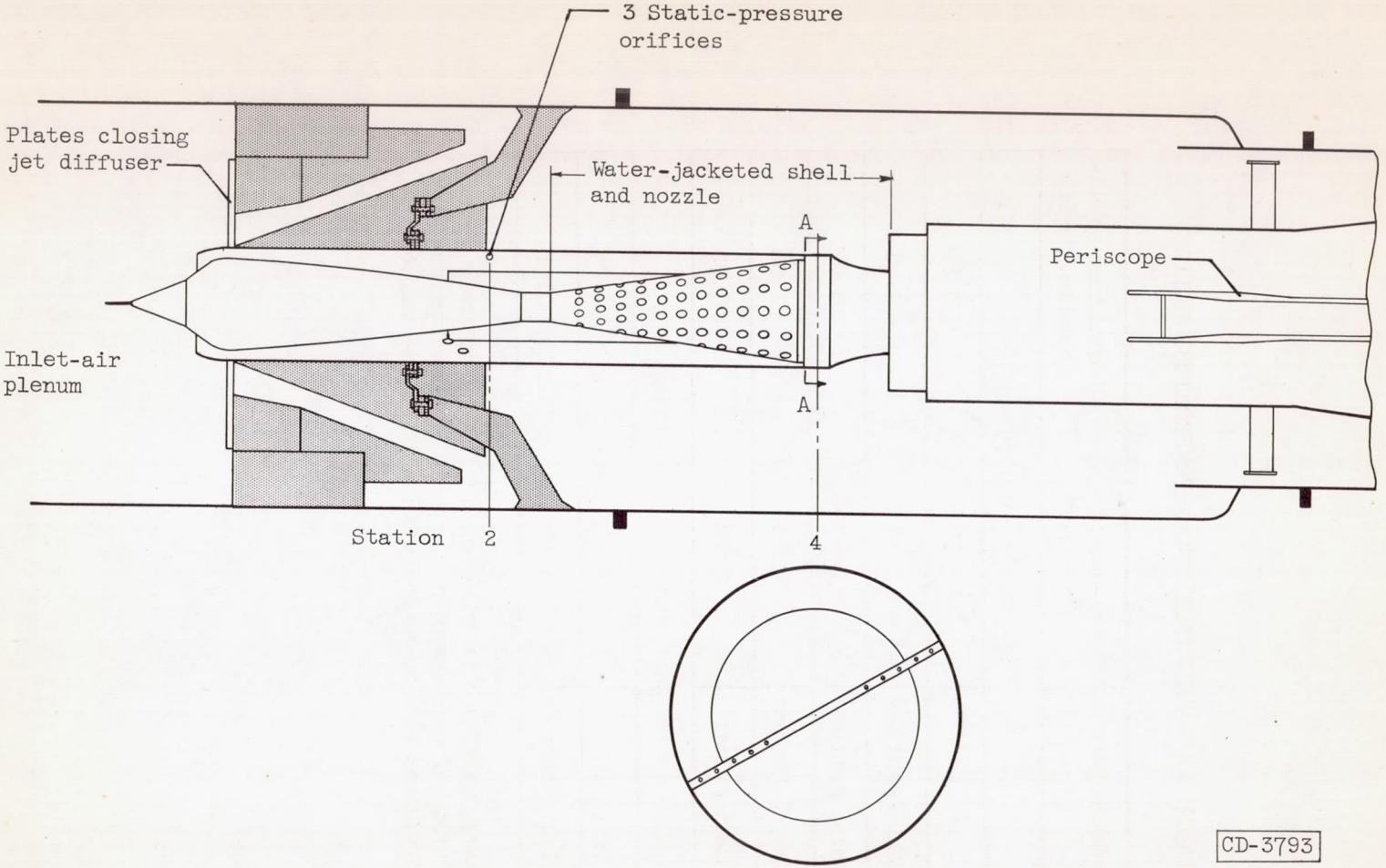
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TABLE I. - SELECTED TOTAL-TEMPERATURE RATIOS[1]

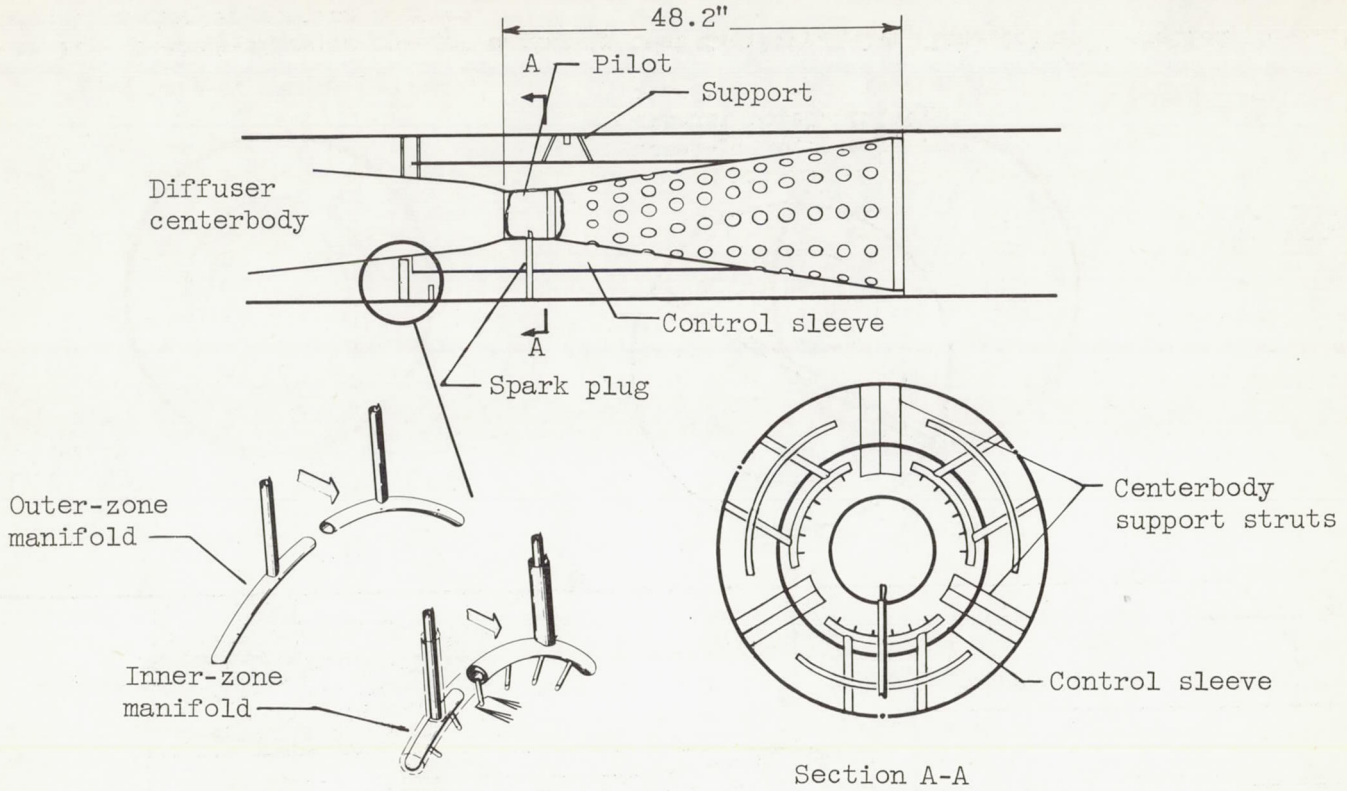
Flame holder	Total-temperature ratio, τ	Combustor total-pressure ratio
86-Inch combustion chamber		
Can	1.95	0.89
2-Ring V-gutter	2.32	0.91
Sloping gutter	1.99	0.96
1-Ring V-gutter	2.26	0.96
Annular pilot	2.29	0.95
56-Inch combustion chamber		
Can	1.78	0.89
Annular pilot	2.12	0.96

[1] Values selected to give good efficiency over wide range of combustor pressures, and combustor total-pressure ratios associated with those values.



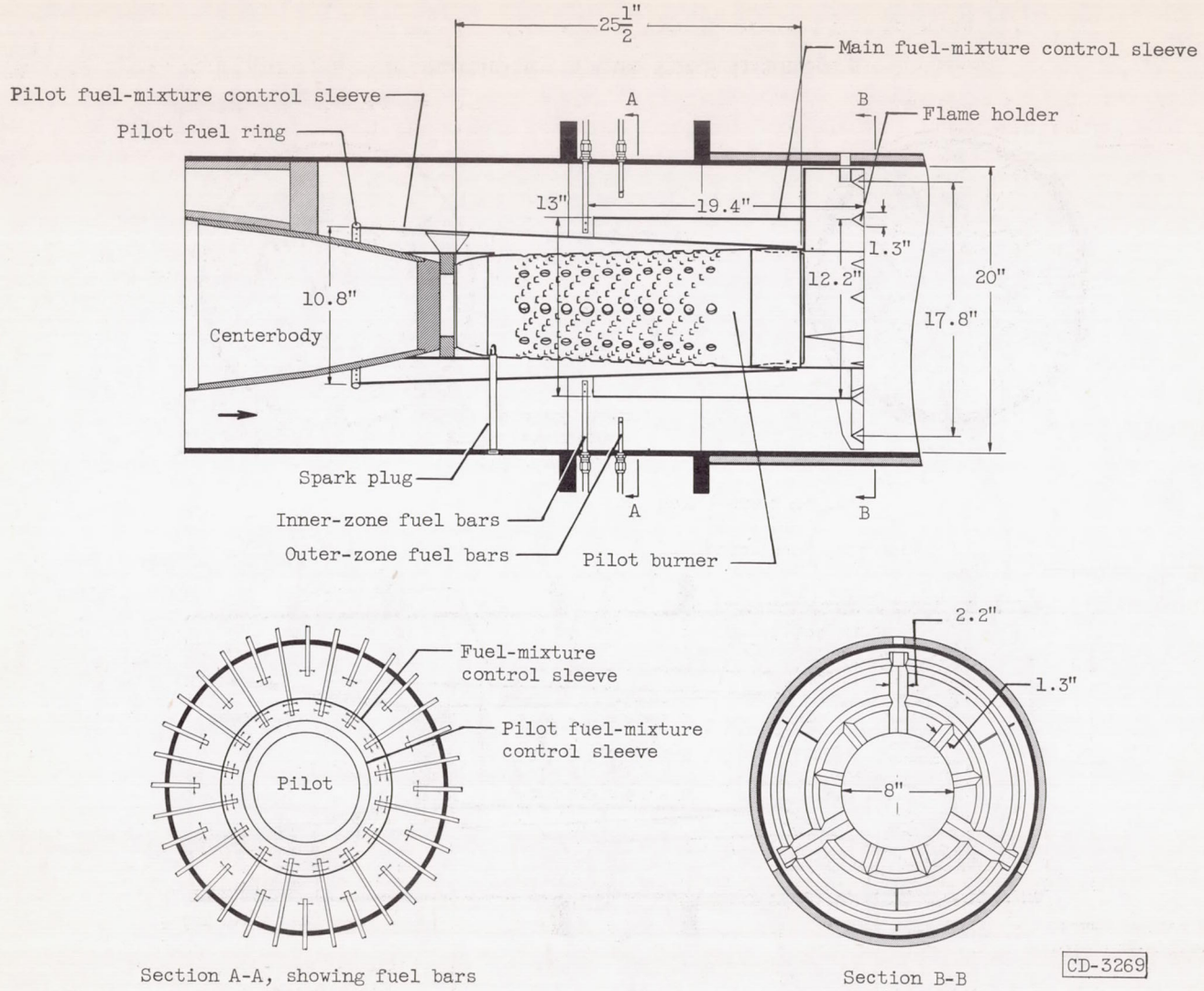
Section A-A
Total-pressure rake at exhaust-nozzle inlet, station 4

Figure 1. - 20-Inch-diameter ram-jet engine in test facility. Can flame holder installed; 30-inch combustion-chamber section removed.



(a) Can flame holder, with fuel-air-mixture control sleeve and fuel system.

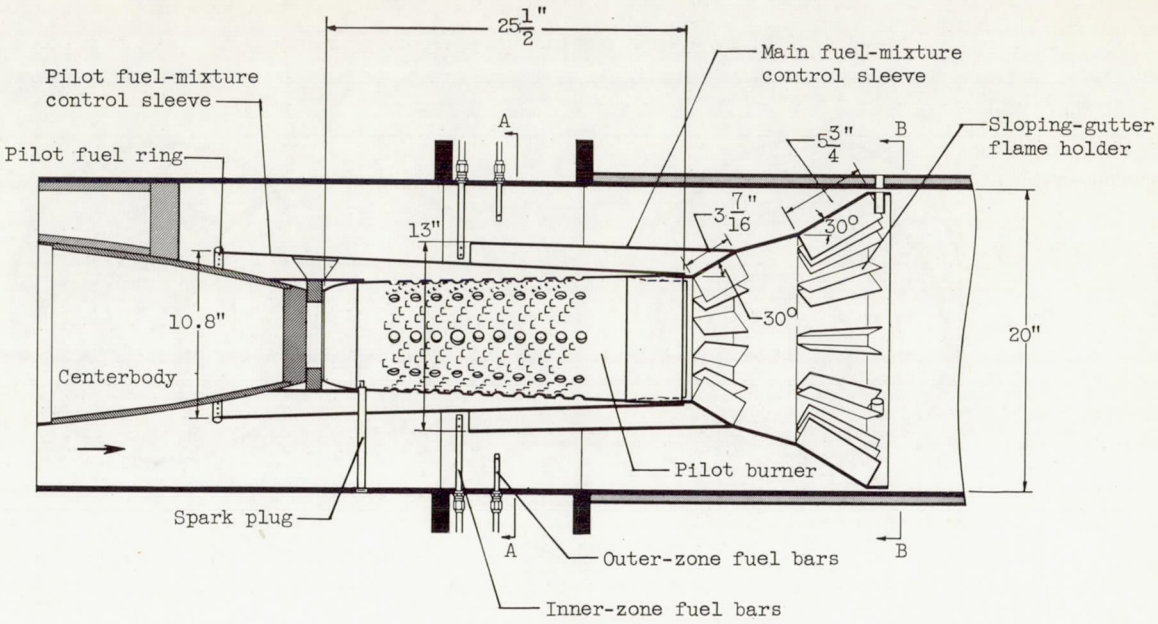
Figure 2. - Flame holders and fuel injectors.

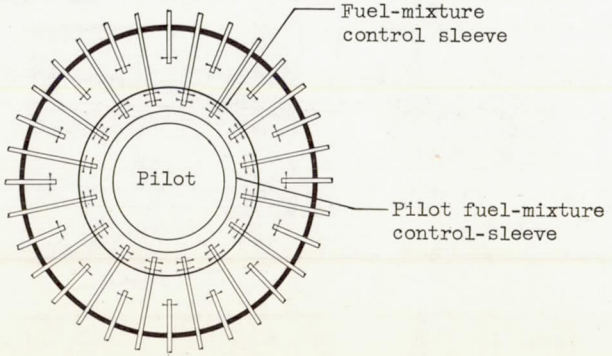


(b) Two-ring V-gutter flame holder with large central pilot burner.

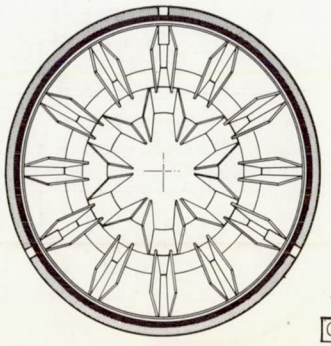
Figure 2. - Continued. Flame holders and fuel injectors.

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Section A-A, showing fuel bars

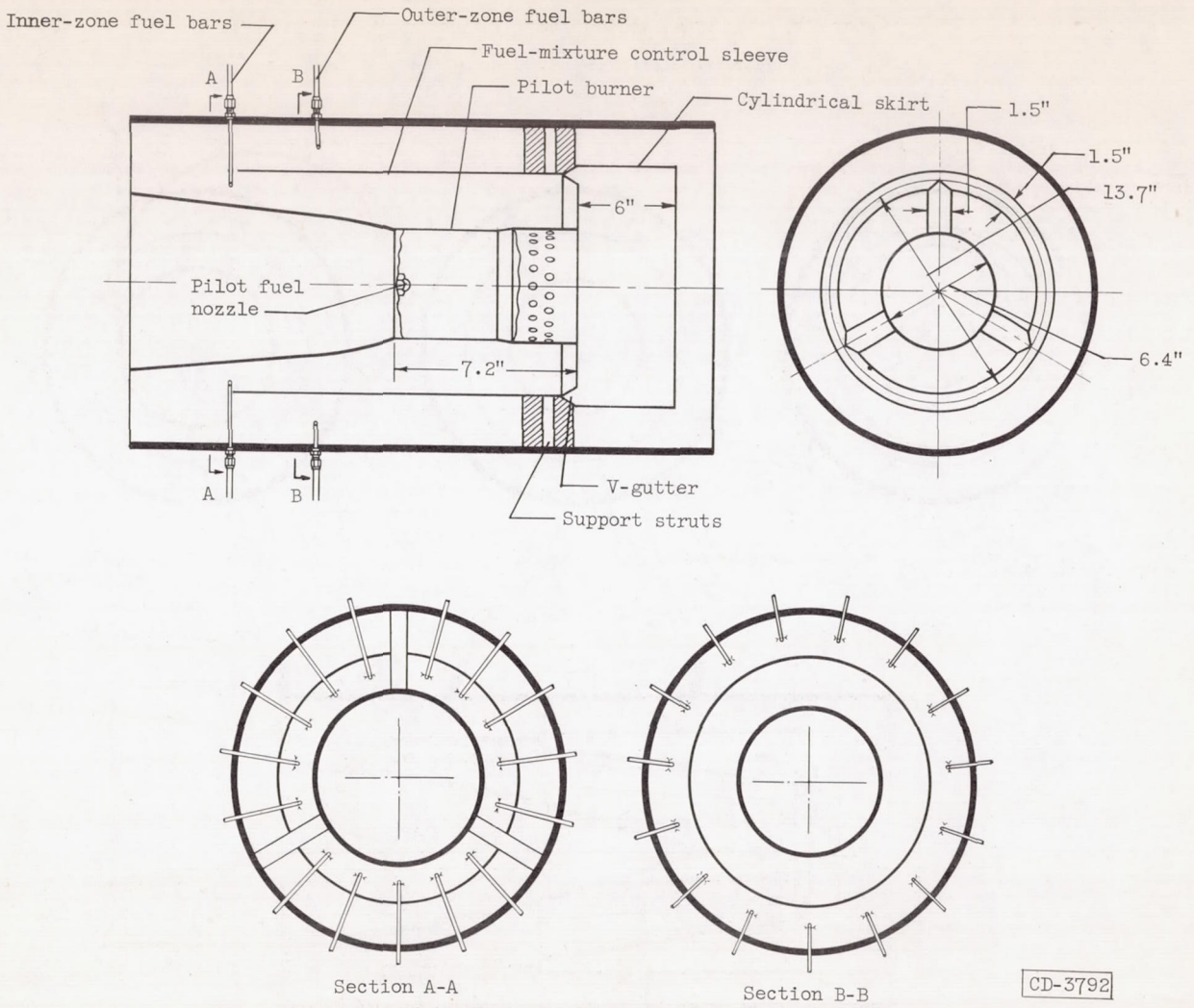


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Section B-B

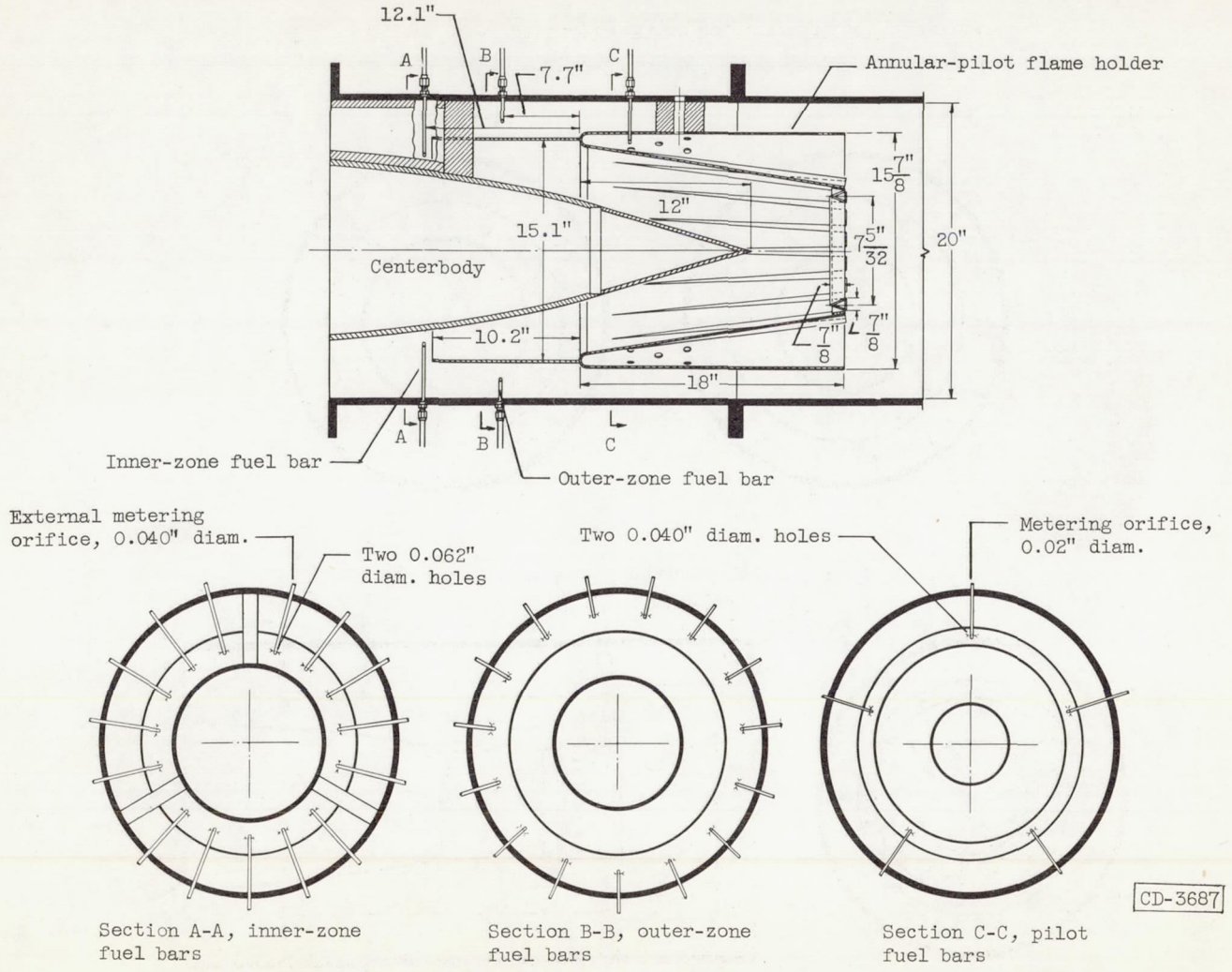
(c) Sloping-gutter flame holder with large pilot burner.

Figure 2. - Continued. Flame holders and fuel injectors.



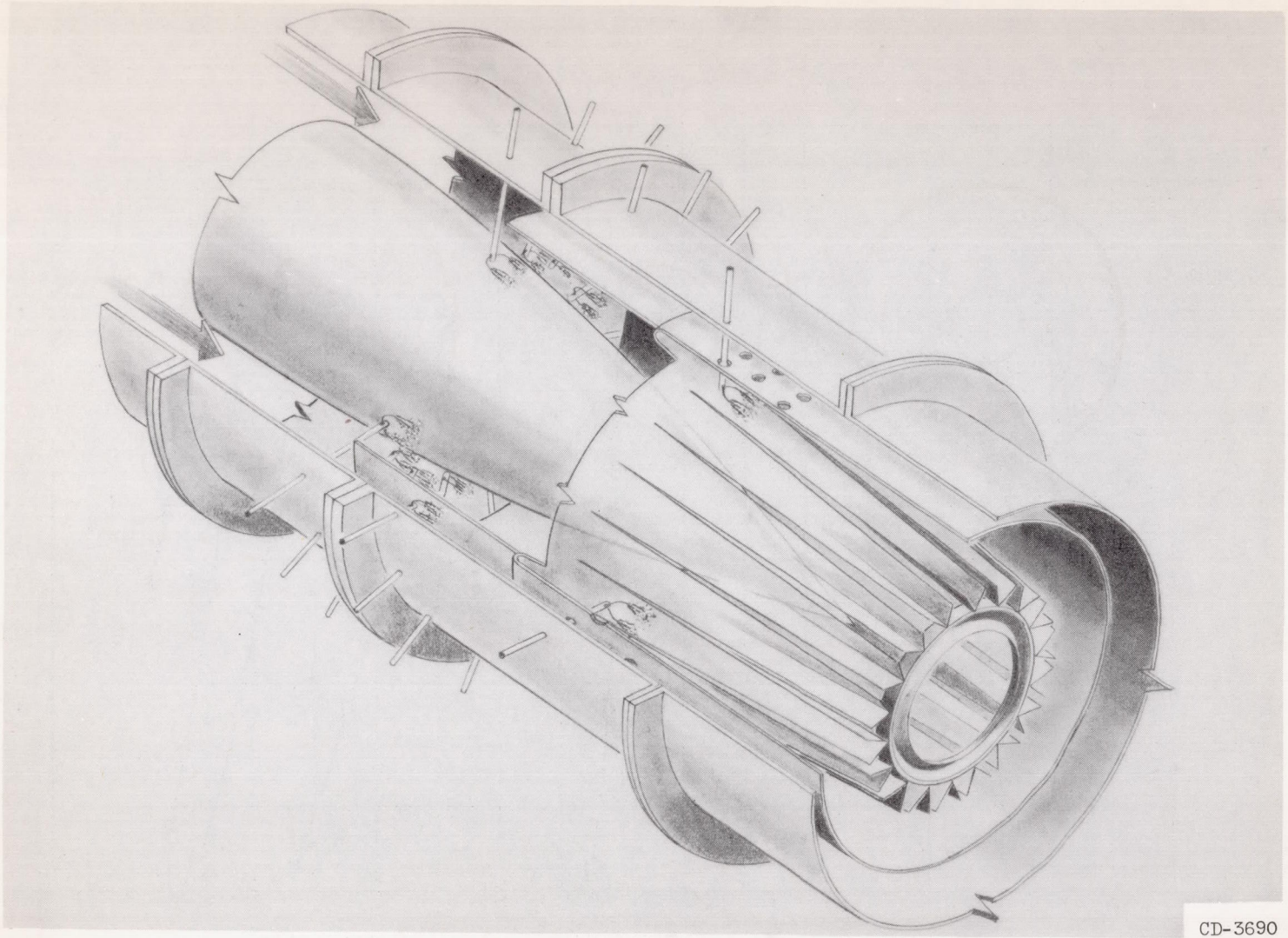
(d) One-ring V-gutter flame holder.

Figure 2. - Continued. Flame holders and fuel injectors.



(e) Annular-pilot flame holder.

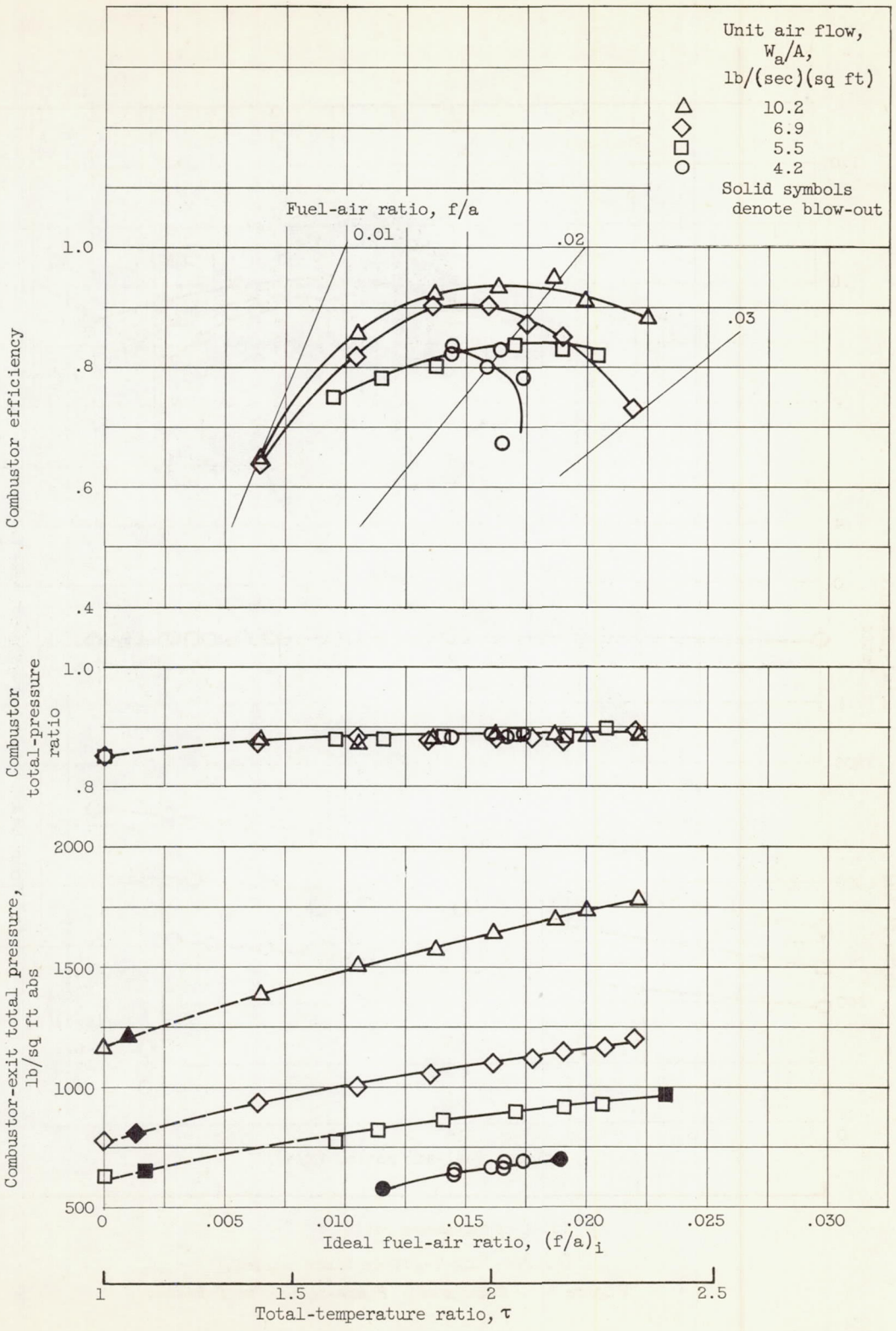
Figure 2. - Continued. Flame holders and fuel injectors.



(e) Concluded. Annular-pilot flame holder.

Figure 2. - Concluded. Flame holders and fuel injectors.

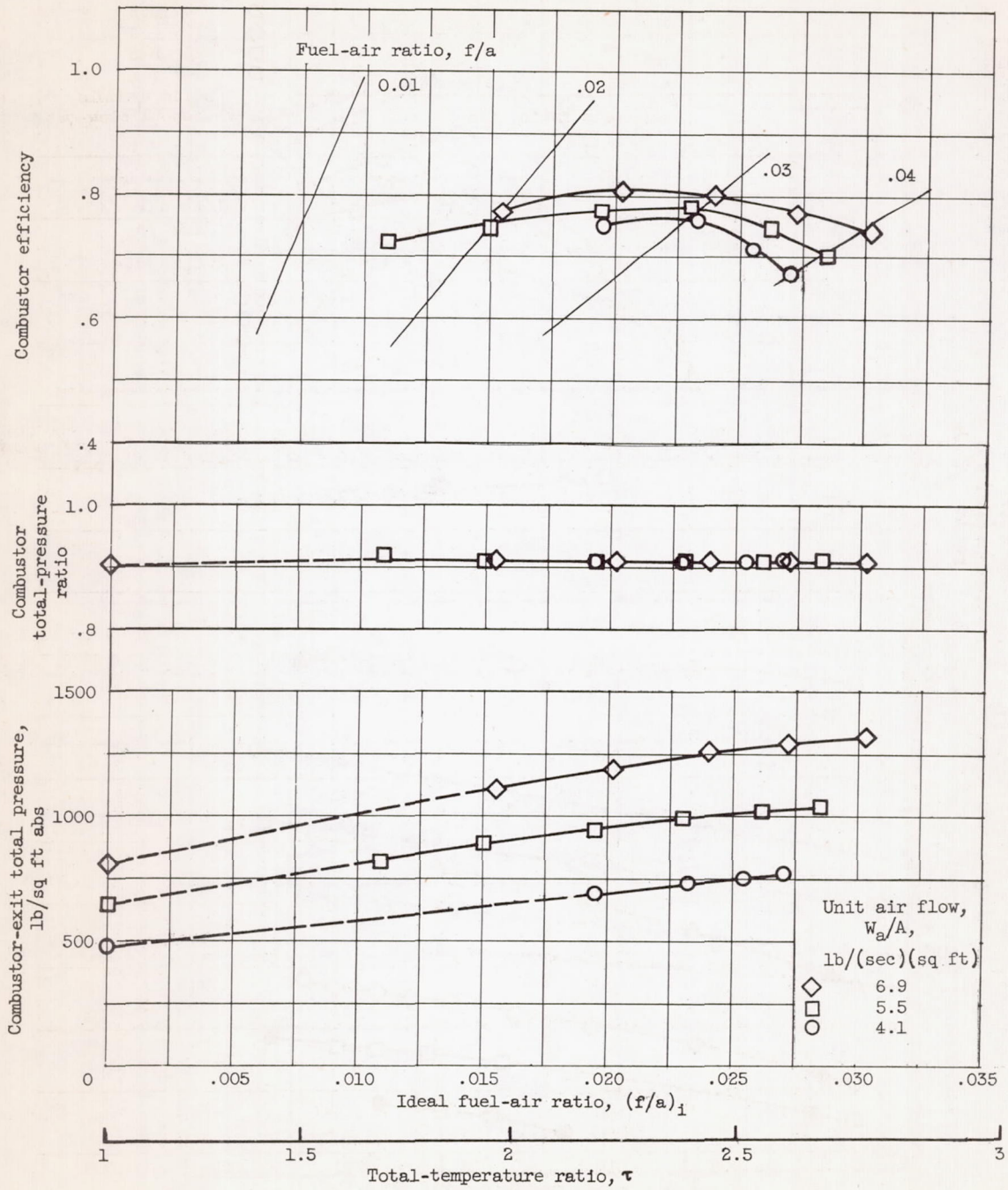
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(a) Can flame holder.

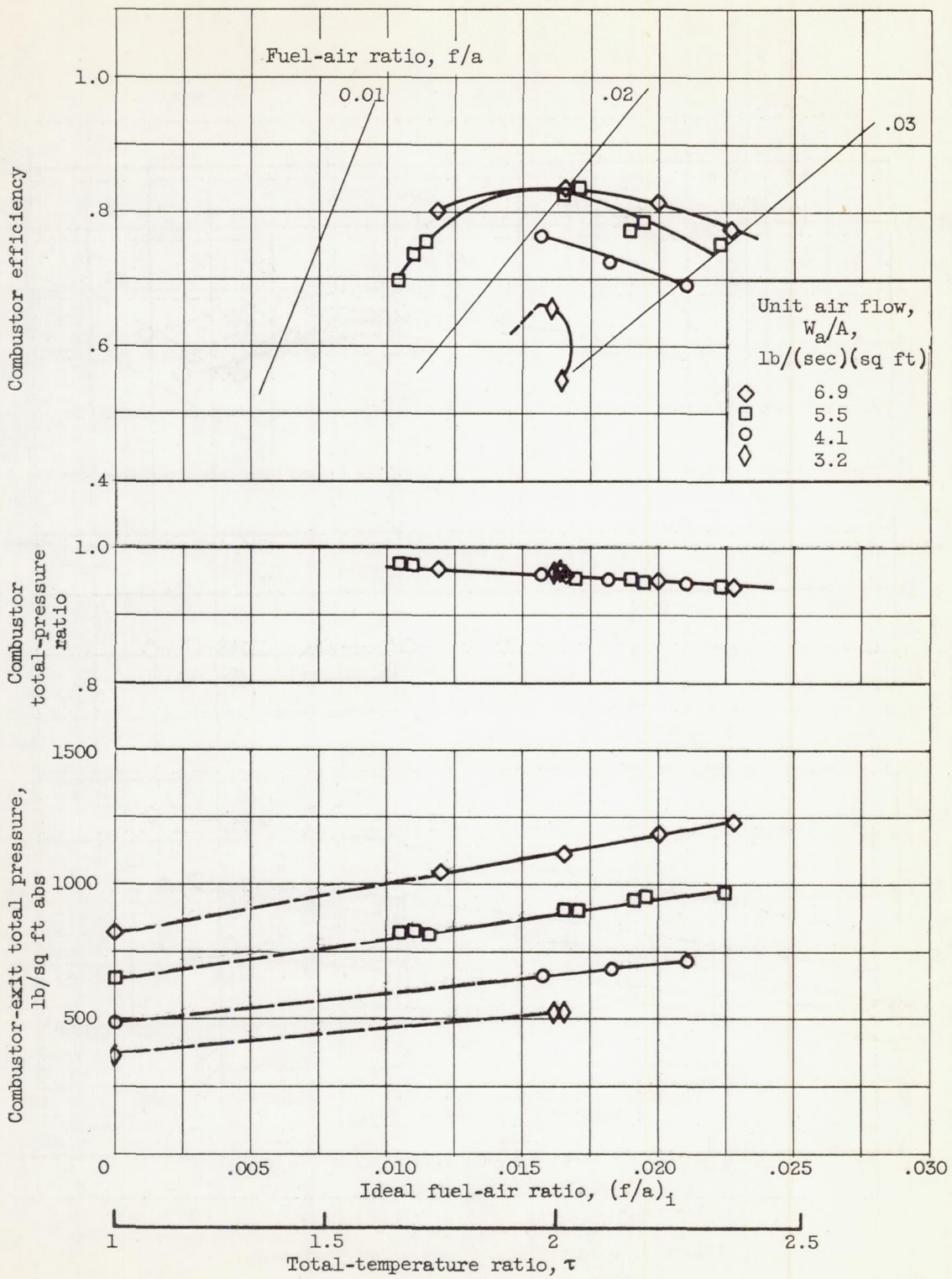
Figure 3. - Flame-holder performance.

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(b) Two-ring V-gutter flame holder.

Figure 3. - Continued. Flame-holder performance.

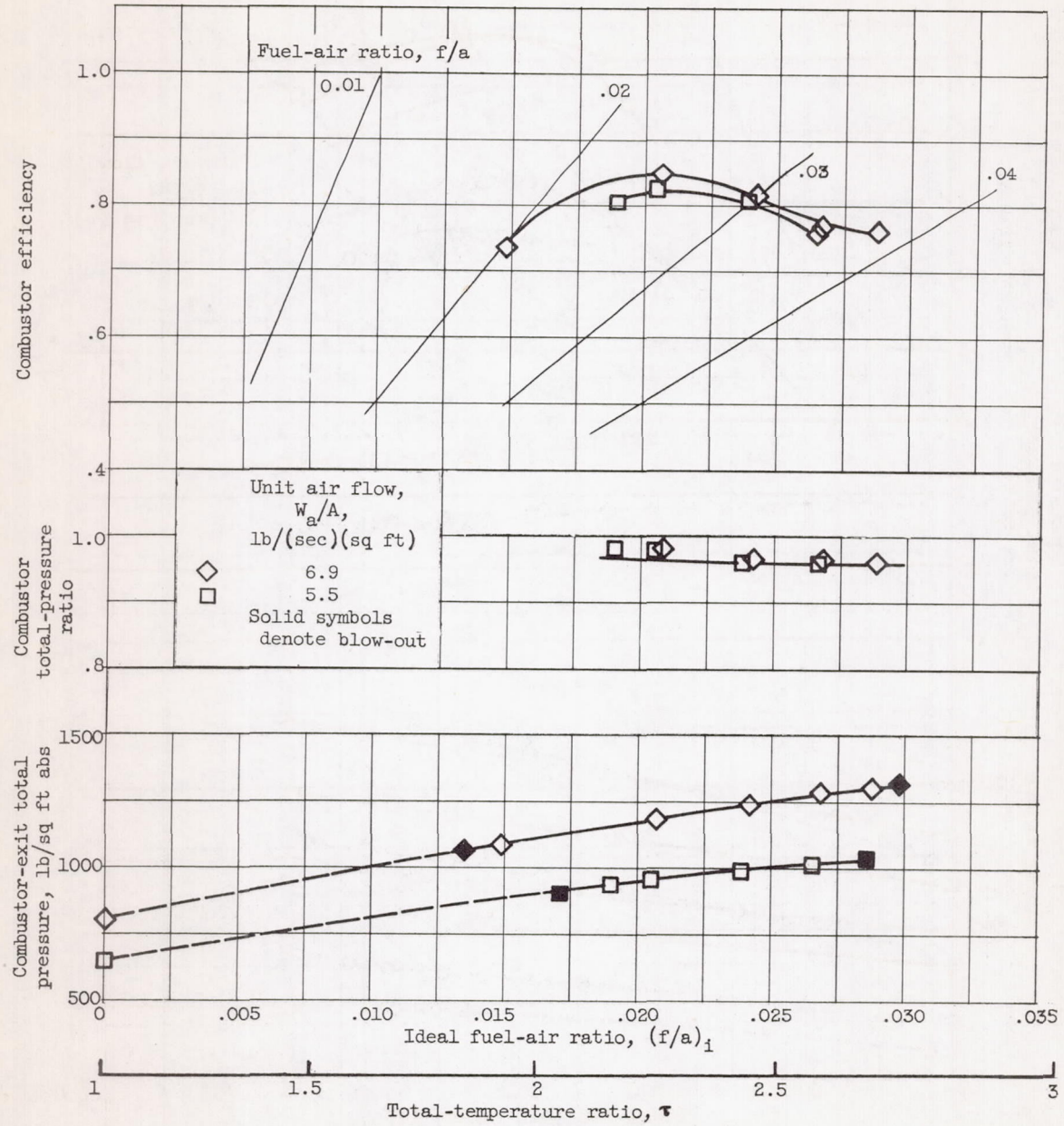


(c) Sloping-gutter flame holder.

Figure 3. - Continued. Flame-holder performance.

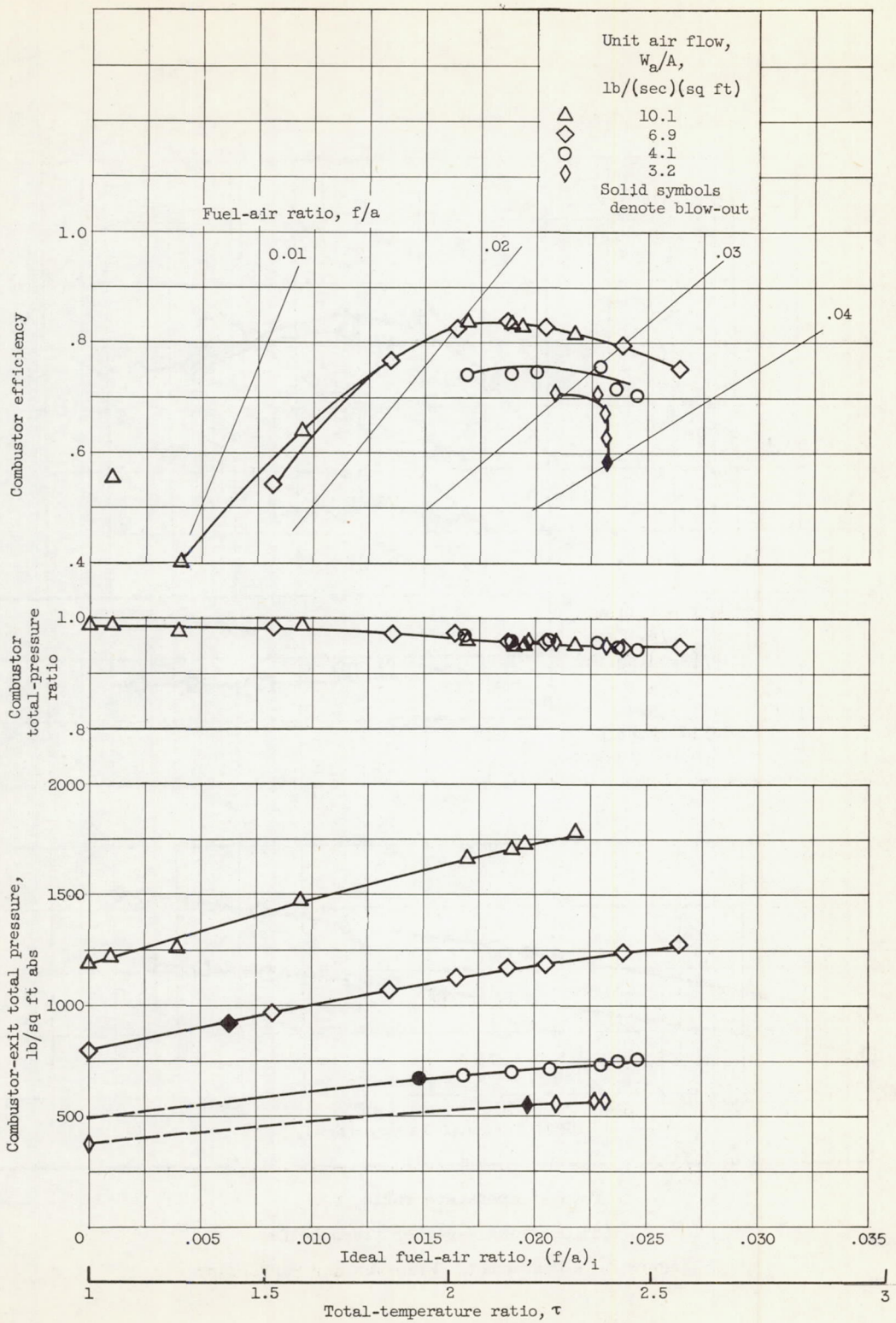
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(d) One-ring V-gutter flame holder.

Figure 3. - Continued. Flame-holder performance.



(e) Annular-pilot flame holder.

Figure 3. - Concluded. Flame-holder performance.

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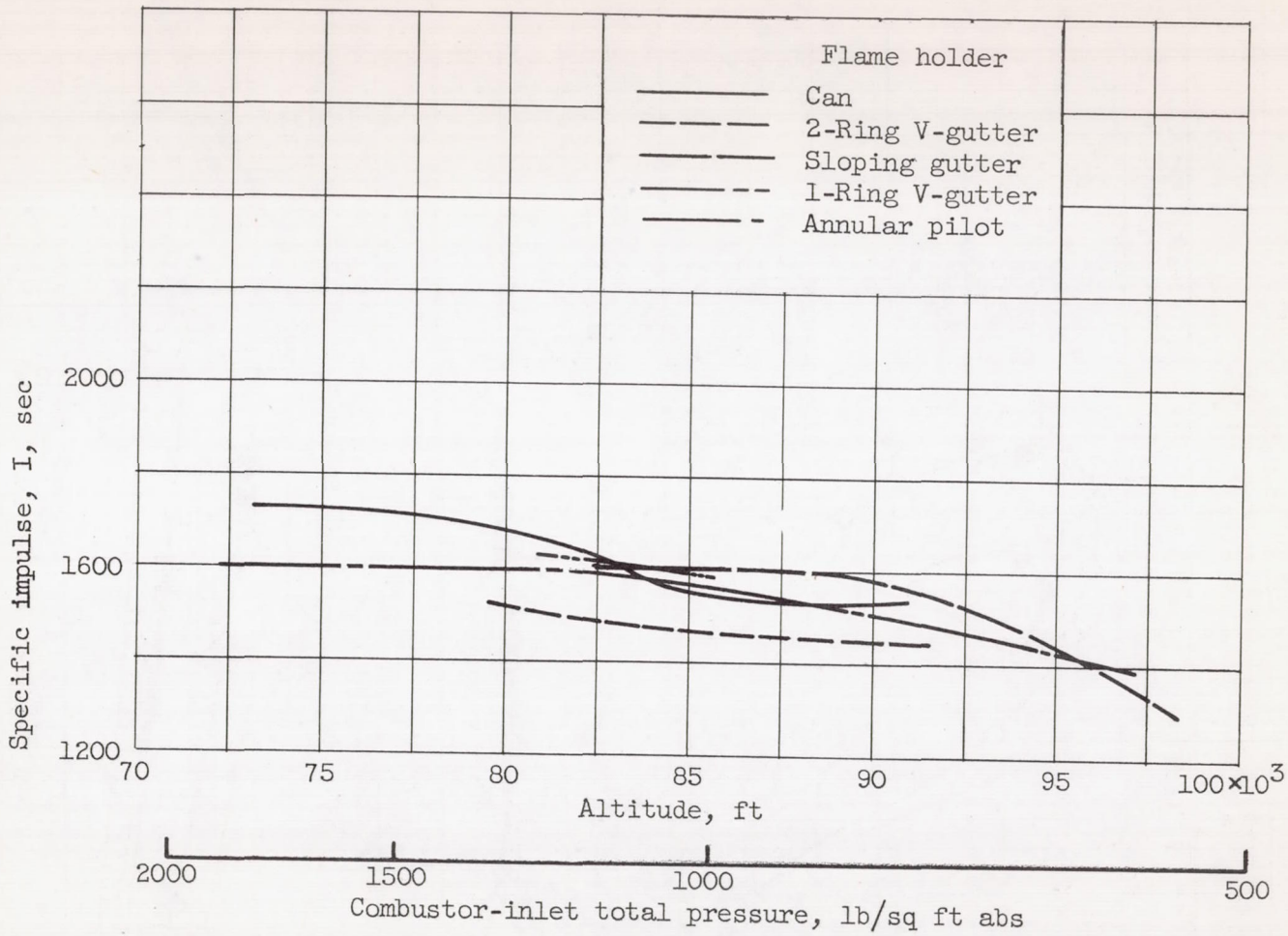
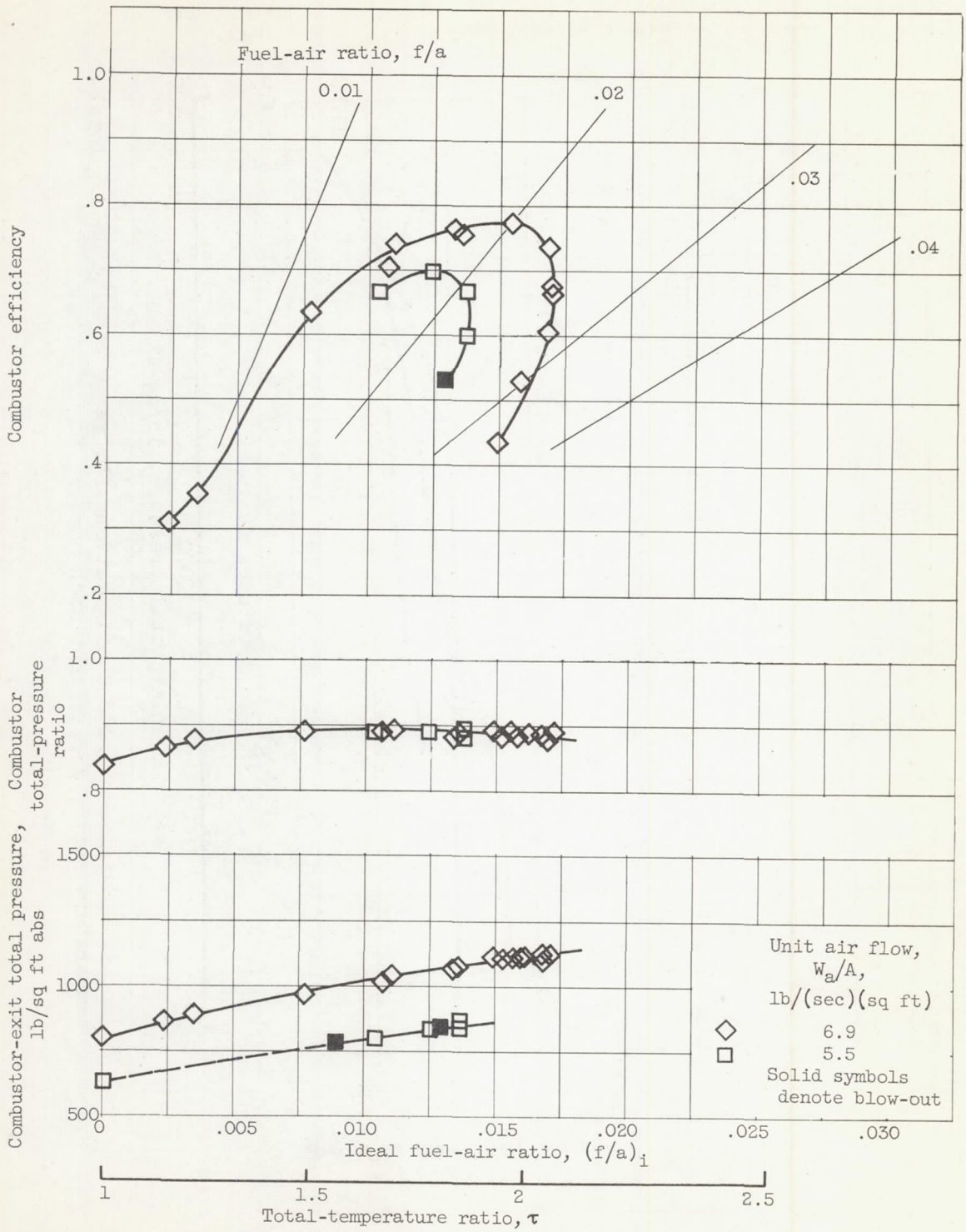
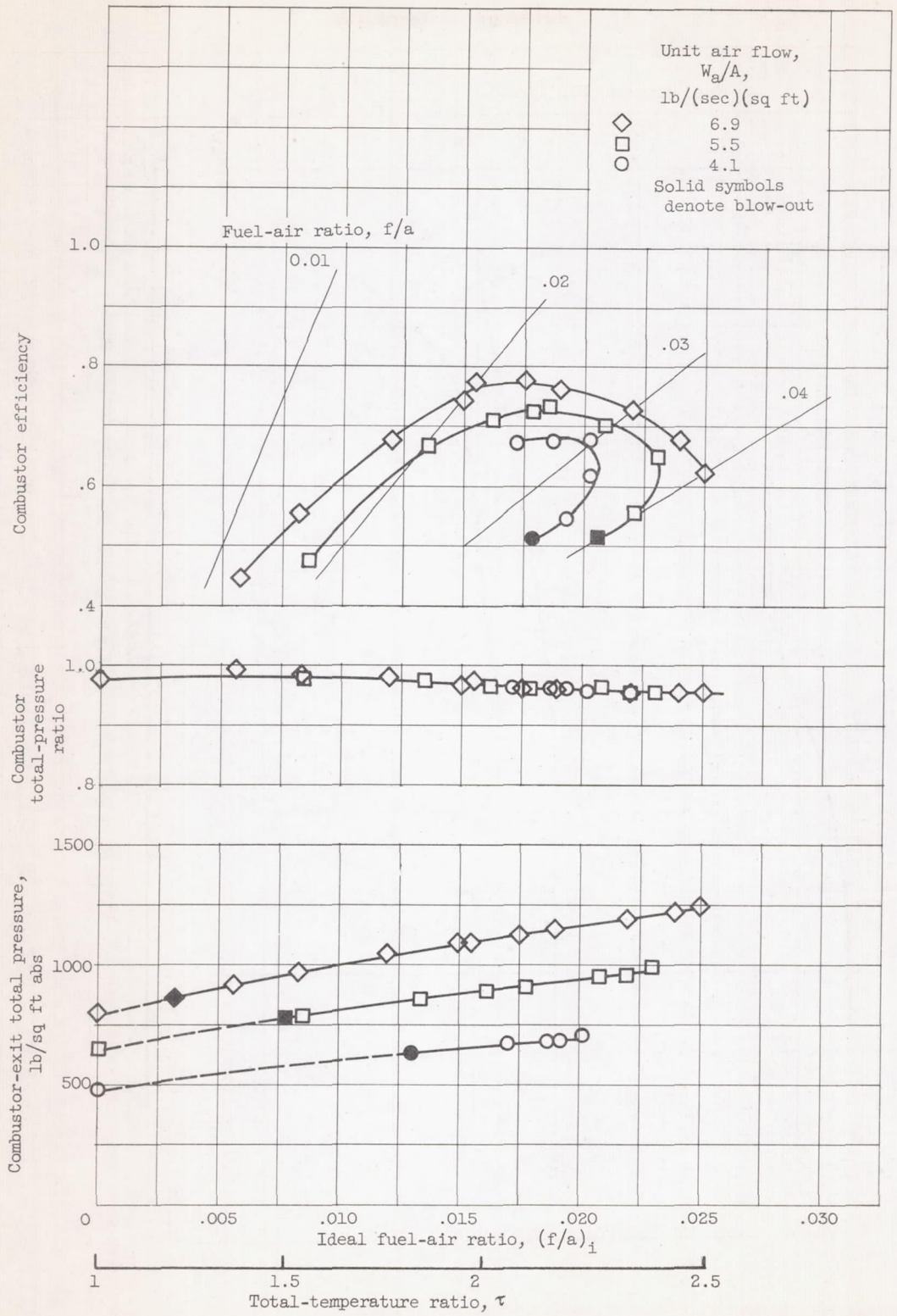


Figure 4. - Impulse of five configurations for range of altitudes. Total-temperature ratio, 2.0; flight Mach number, 3.



(a) Can flame holder.

Figure 5. - Performance of flame holders with short combustion chambers.



(b) Annular-pilot flame holder.

Figure 5. - Concluded. Performance of flame holders with short combustion chambers.

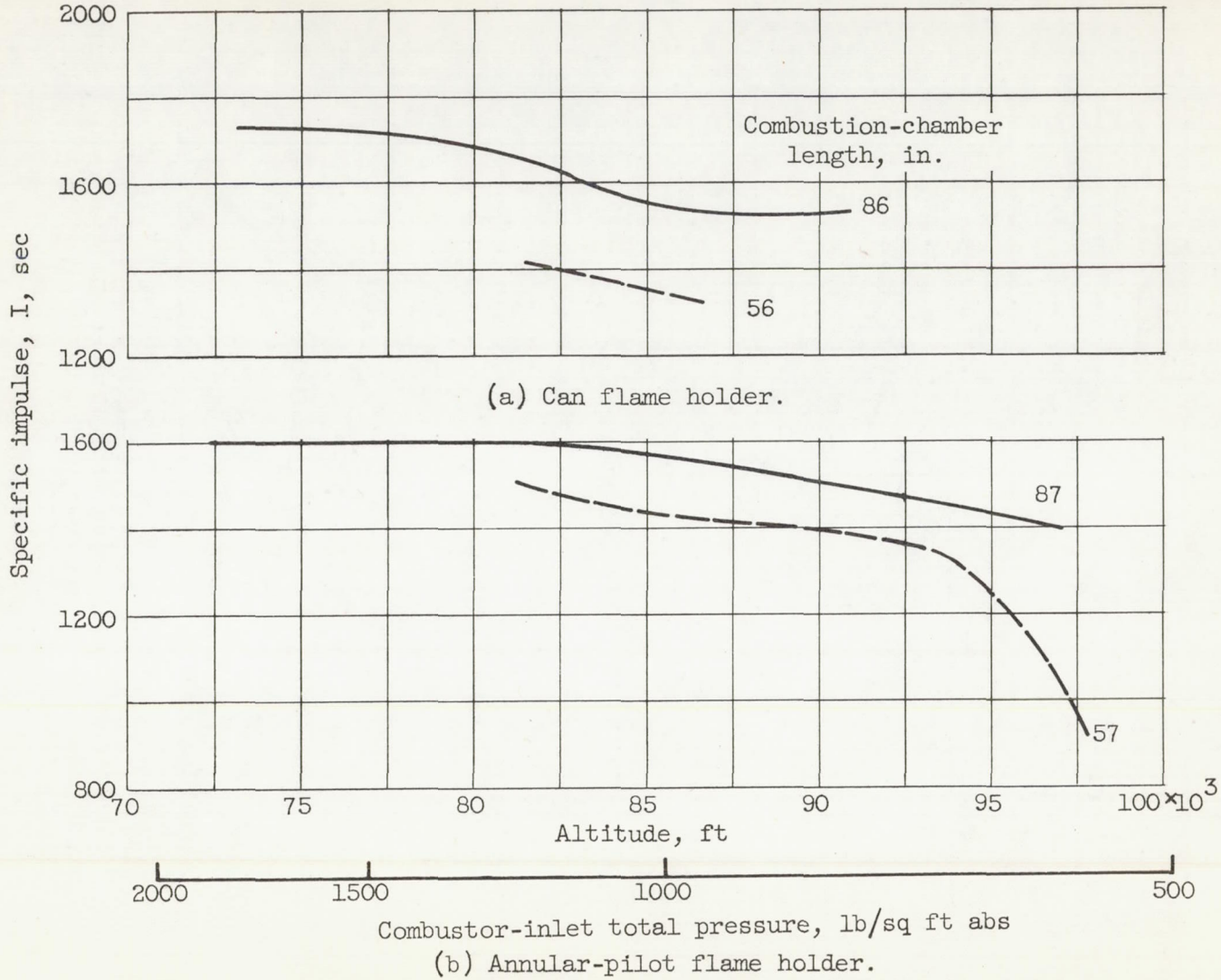


Figure 6. - Effect of combustion-chamber length on performance of two flame-holder configurations. Total-temperature ratio, 2.0; flight Mach number, 3.

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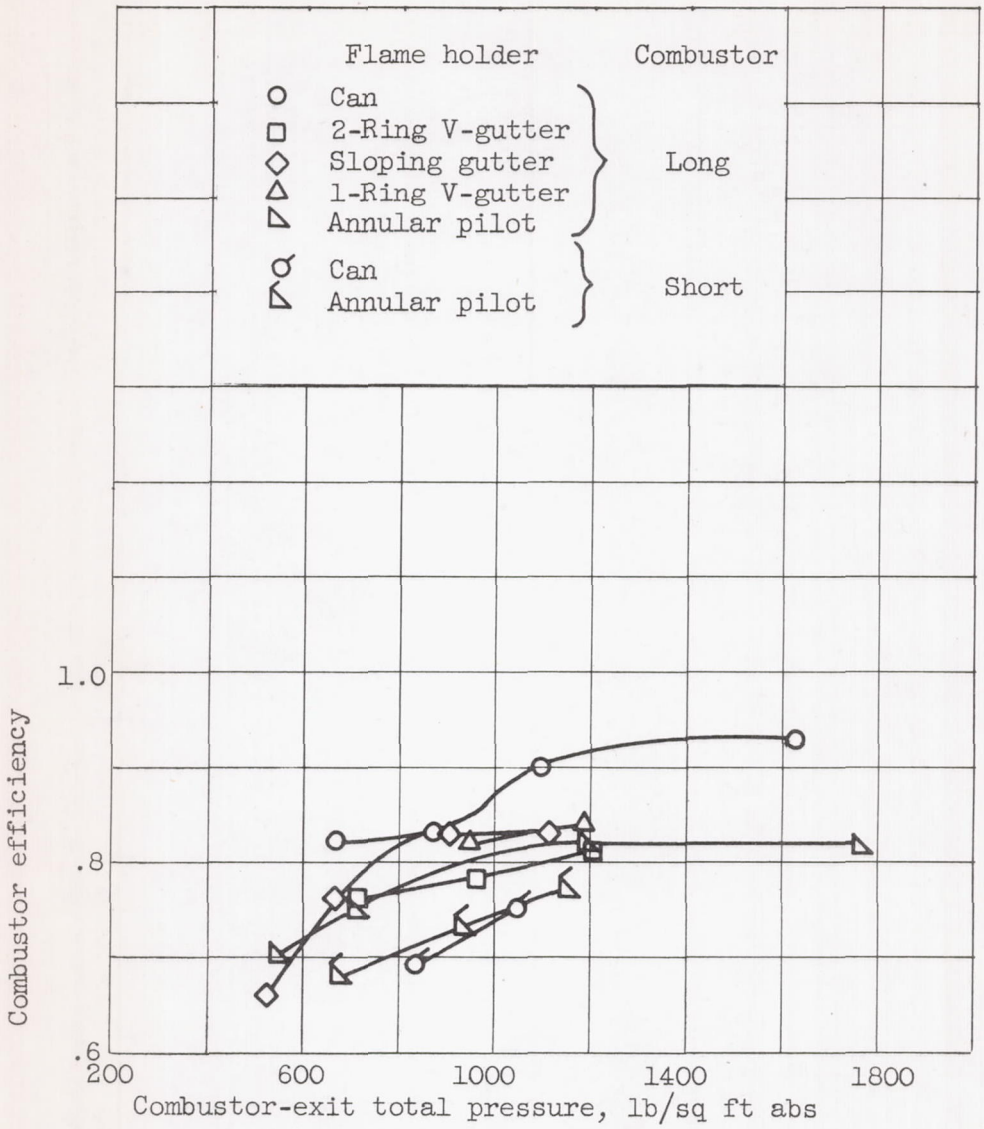


Figure 7. - Combustor efficiencies and combustor-exit total pressures associated with total-temperature ratios selected to represent performance of each flame holder.